United States
Environmental
Protection Agency

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and Development
Washington, DC 20460

EPA/530-SW-87-021I
June 1987

EPA

Municipal Waste Combustion Study

Recycling of Solid Waste

June 1987

MUNICIPAL WASTE COMBUSTION STUDY:

RECYCLING OF SOLID WASTE

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EPA Contract No, 68-02-4330, Work Assignment 9
Radian Project No. 239-001-09

DISCLAIMER

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1. INTRODUCTION AND SUMMARY

This report is an assessment of recycling of solid waste as an alternative or augmentative waste management strategy to municipal waste combustion. The information presented in this report was developed as part of a comprehensive, integrated study of municipal waste combustion. An overview of the findings of this study may be found in the Report to Congress on Municipal Waste Combustion (EPA/530-SW-87-021a). Other technical volumes issued as part of the Municipal Waste Combustion Study include:

- Emission Data Base for Municipal Waste Combustors (EPA/530-87-SW-021b)
- Combustion Control of Organic Emissions (EPA/530-SW-87-021c)
- Flue Gas Cleaning Technology (EPA/530-SW-87-021d)
- Cost of Flue Gas Cleaning Devices (EPA/530-SW-87-021e)
- Sampling and Analysis of Municipal Waste Combustors (EPA/530-SW-87-021f)
- Assessment of Health Risks Associated with Exposure to Municipal Waste Combustion Emissions (EPA/530-SW-87-021g)
- Characterization of the Municipal Waste Combustion Industry (EPA/530-SW-87-021h)

As landfill areas available for municipal waste disposal have become increasingly scarce, renewed interest has been generated in volume reduction as a part of waste management. A great deal of emphasis has been placed on combustion as a waste volume reduction method, but there has also been an increased interest in recycling materials that would otherwise end up in landfills. While recycling is not expected to eliminate the need for combustion, it is being increasingly seen as a possibility for augmenting the volume reduction achieved through combustion.

Although the United States is not as active in the area of materials recycling from waste as are some other countries, in 1984 about 10 percent of material that would otherwise have ended up in disposal facilities was recovered and reused. Most of the recovery in the United States was accomplished through source separation, that is, manual separation by the generator, rather than separation from mixed refuse in centralized waste processing facilities. There are thousands of source separation programs in operation across the United States including 400 to 500 curbside recycling programs. Some states, particularly in the Northeast, have made participation mandatory. Added to the source separation programs, there are some 30 to 40 centralized waste processing plants, separating materials from mixed refuse. These plants are producing refuse-derived fuels and, in the process, are removing mostly non-combustibles from the waste.

Centralized processing methods are becoming increasingly sophisticated and effective at separating waste materials. A notable state-of-the-art system developed in Europe, the Sorain-Cecchini process, is an integrated recovery system that can produce paper pulp, animal feed, compost, aluminum scrap, ferrous scrap, densified refuse derived fuel, and pelletized polyethylene for production of sheet plastic used in garbage bags. A similar process known as Stardust '80 has been developed and commercially demonstrated in Japan. Moreover, plans are currently underway to construct integrated waste recovery facilities in the United States based on the ORFA process.

Methods for separation and uses for recovered materials have been established for paper, glass, scrap ferrous metals, aluminum, wood waste, yard waste, and rubber. Also, separation methods and markets for recovered plastics are currently the subject of rapidly advancing research. At the present time, technical and economic factors combine to make paper and aluminum the most extensively recycled materials from U.S. waste.

Recycling, as a part of an overall waste management strategy, should be a positive measure for most localities. In general, recycling of noncombustible materials would have a positive effect on combustion operations, allowing the potential for smaller facilities, more reliable operation, and decreased ash handling requirements.

The effect of recycling on the feasibility of combustion should be considered, however, in the context of local refuse characteristics. For example, one of the constituents of waste that is widely recycled is paper. Because paper contains the largest portion of the heating value in the waste, recycling goals for paper should be consistent with combustor design heating value requirements. Due to site-specific variations in refuse composition, markets for recycled materials, combustor design option limitations, and other factors, judgements on the optimum combination of recycling and combustion for a given waste management plan are most appropriately made on a site-specific basis.

In addition to augmenting the volume reduction achievable through combustion of municipal waste, recycling may provide an opportunity for reducing emissions of hazardous materials resulting from combustion or direct landfill of certain waste materials. In particular, recycling of alkaline batteries, which contain about 1 percent by weight of mercury, represents a potential means of substantially reducing mercury emissions from municipal waste combustors. In Sweden, it is estimated that two-thirds of mercury emissions from municipal waste combustors would be eliminated by recycling alkaline batteries. This is significant in light of the fact that emissions tests of state-of-the-art control technologies applied to municipal waste combustors have demonstrated only 30 to 40 percent control of mercury emissions. (See "Municipal Waste Combustion Study: Emission Data Base for Municipal Waste Combustors;" EPA/530-SW-87-02/b.) Furthermore, to the extent that combustion conditions are improved through removal of noncombustible materials, pollutants resulting from the combustion process (e.g. organics, carbon monoxide) should also be reduced through recycling of noncombustibles.

Strategies for reducing emissions of other pollutants from municipal waste combustion by removing materials from the waste are not as easily discernible. For example, measurements at one test facility showed reduction in lead and cadmium emissions when metals and glass are removed from the waste prior to combustion. Metals such as cadmium, lead, and chromium, however, are contained in paints, colorants, and stabilizers are distributed throughout the combustible portions of the waste. Therefore, elimination of their emissions through removal does not appear likely. Further, the major sources of chlorine in the waste, and hence the sources of substantial quantities of HCl emissions, are paper and plastics. But these materials also have the highest heating values of the materials in the waste, so their total removal would not be practical. Finally, removal of polyvinyl chloride (PVC) from the waste has been suggested as a strategy for reducing emissions of chlorinated dibenzo-p-dioxins (CDDs) and chlorinated dibenzofurans (CDFs). The mechanisms for formation of CDDs and CDFs in the combustion of waste are not thoroughly understood at this time. While research shows that PVC can act as a precursor in CDD/CDF formation, it is thought that other materials in the waste may also participate in chemical reactions leading to CDD/CDF formation. Therefore, the effectiveness of reducing CDD/CDF through removal of PVC is not clear.

In this report background information on recycling, its status in the United States and abroad, and its technical feasibility are examined. Also, because recycling is expected to be an integral part of a solid waste management plan that includes combustion, potential effects on combustion of removing materials from the waste are considered. This report resulted from a brief investigation of a subject area in which a lot of things are happening. Thus, it is designed to convey a sense of the current status of recycling and its technical feasibility, rather than to embody comprehensive authoritative reference material.

In Section 2, the current extent of recycling in the United States and in several other countries is reviewed. The material on the current recycling programs and approaches is followed by two sections on feasibility of recycling. Section 3 contains information on methods for separation of materials and Section 4 contains information on uses and markets for recovered materials. Finally, Section 5 seeks to address questions concerning the effects of recycling activities on combustion processes.

This work was performed by Radian Corporation under EPA Contract 68-02-4330, Work Assignment 9. EPA's Work Assignment Manager was Mr. David Cleverly of the Strategies and Air Standards Division of the Office of Air Quality Planning and Standards.

2. EXTENT OF CURRENT RECYCLING

2.1 RECYCLING IN THE UNITED STATES

Recycling in the United States is on the increasing, as shown in Figure 2-1.[1] The quantities represented in the figure are reportedly conservative, so that further increases in recycling and recovery activities would cause an increase in the materials recovery segment shown. In 1984 total material recovery amounted to about 10 percent of total discarded material, as shown in Table 2-1. This is compared to about 25-30% of municipal waste that has been described as "easily" recyclable.[2] Most of the recovery to date has been accomplished through source separation.[3,4]

There is a movement underway in the U.S. to increase source separation of constituents in municipal refuse. Recycling programs are being developed by State and Local governments throughout the United States, but particularly in the Northeast where land for disposal is scarce. The number of such recycling programs is estimated in the thousands.[5]

There are 400 to 500 curbside recycling programs of various sizes operating across the country with a growing number, particularly in the Northeast, stipulating mandatory participation.[6] Typical participation rates for voluntary curbside collection programs in the United States are reported to be about 33 percent.[7] Some programs, however, report much higher voluntary participation rates. For example, a voluntary curbside recycling program in San Jose, California reports 70 percent participation, while another program in Kitchener, Ontario (Canada)[8] reports 80 percent participation. Sixty-eight municipalities in Pennsylvania report an average participation rate of 54 percent[9] and, Woodbury Township in New Jersey reports recycling 45 percent of its waste.[10] Voluntary residential curbside collection programs are estimated to reduce the amount of waste discarded in a service area by about 8 percent. This estimate is based on a typical 33 percent participation rate and assumes recyclables account for about one quarter of most residential waste.

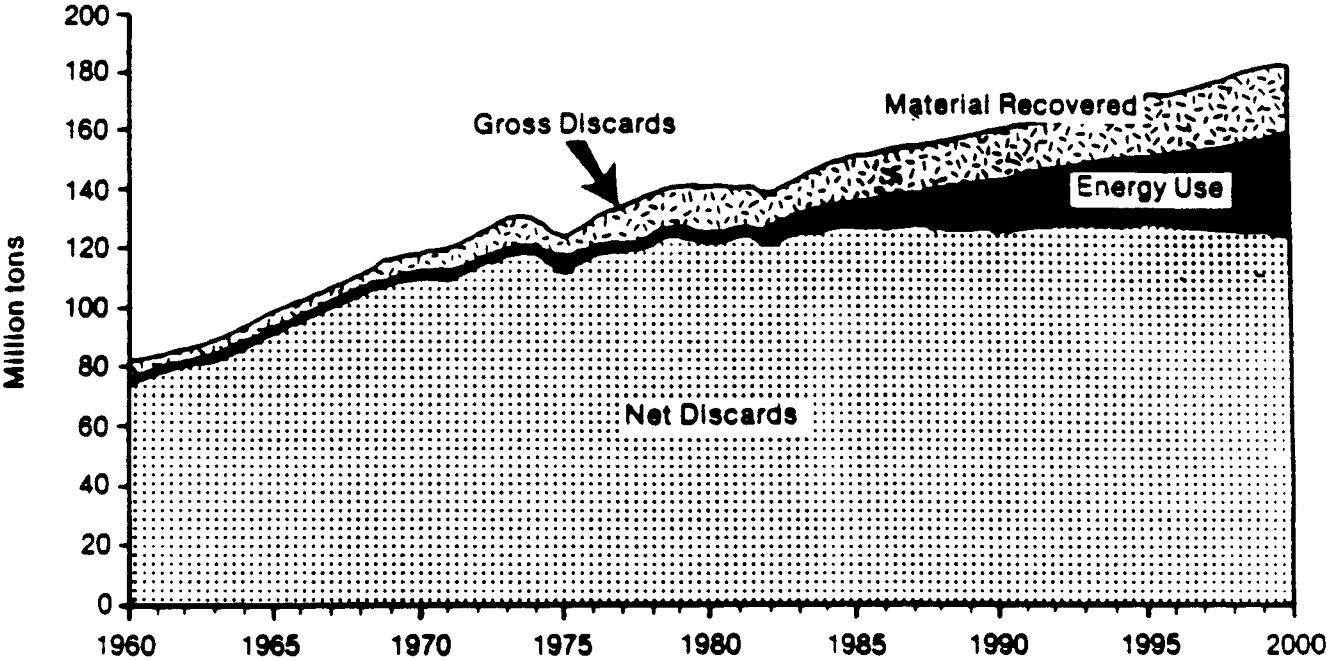

Figure 2-1. Gross discards, materials recovery, energy recovery, and net discards of municipal solid waste, 1960 to 2000.[1]

TABLE 2-1. DISCARDS AND RECOVERY OF MATERIALS IN THE MUNICIPAL WASTE STREAM, 1984[1]

(In millions of tons and percent)

Materials	Gross Discards	% of Discards	Postconsumer Materials Recovery	Net Discards	% of Discards
Paper and Paperboard	62.3	42.1	12.9	49.4	37.1
Glass	13.9	9.4	1.0	12.9	9.7
Metals					
Ferrous	11.3	7.6	0.3	11.0	8.3
Aluminum	2.1	1.4	0.6	1.5	1.1
Other Nonferrous	0.3	0.2	0.0	0.3	0.2
Plastics	9.7	6.5	0.1	9.6	7.2
Rubber and Leather	3.4	2.3	0.1	3.3	2.5
Textiles	2.8	1.9	0.0	2.8	2.1
Wood	5.1	3.4	0.0	5.1	3.8
Other	0.1	0.1	0.0	0.1	0.1
TOTAL NONFOOD PRODUCT WASTES	111.1	75.0	15.1	96.0	72.2
Food Wastes	10.8	7.3	0.0	10.8	8.1
Yard Wastes	23.8	16.1	0.0	23.8	17.9
Miscellaneous Inorganic Wastes	2.5	1.7	0.0	2.5	1.9
TOTAL WASTES DISCARDED	148.1	100.0	15.1	133.0	100.0

[1] Details may not add to totals due to rounding.

Mandatory programs are currently achieving participation of at least 50 percent and, in some cases, as high as 80 to 90 percent. The proportion of the total waste stream diverted by these mandatory programs is estimated to be 12 to 23 percent.[7] Container deposit laws have resulted in 80 to 95 percent recovery of returnable containers, reducing total waste in areas where they apply by about 5 percent.[2,11] No statistics were found for the amount of waste diverted by central collection centers.

Materials being recovered most successfully in source separation programs include paper, aluminum cans, and glass.

In addition to curbside recycling and source separation programs, there are 30 to 40 centralized materials separation facilities operating in the U.S. These plants are recovering materials for reuse from mixed refuse. Waste Age listed 33 U.S. separation facilities with total design capacity of 41,000 tons per day of waste operating in the U.S. in its November 1985 update.[12] While the list may not be all inclusive, previous experience with this compilation indicates that it probably contains most of the facilities.

2.2 RECYCLING IN OTHER COUNTRIES

2.2.1 Sweden

In Sweden about 40 to 45 percent of domestic waste is landfilled, about 45 to 50 percent is incinerated, and about 10 percent is separated and/or composted in central processing plants. In the period between 1977 and 1982 about 15 to 20 centralized processing plants were built. In the first two years of operation problems occurred with the new, undemonstrated technology. Even bigger problems surfaced in the lack of markets for materials produced in the centralized processing facilities. Meeting the high quality specifications placed on recycled materials has been particularly difficult for recovered materials. Moreover, refuse derived fuel (RDF) produced by the processing plants has not been successfully burned in equipment designed and built for burning other solid fuels. Compost produced in the centralized plants has also been difficult to market because of its glass and plastic content. Recent reports say that the compost is currently being used as landfill cover. Still, with all the problems, progress is being made as shown in Table 2-2, and the Swedish government is continuing to encourage and promote recycling of municipal waste.[13]

Because of the negative experience with centralized separation plants, there has been a growing interest in source separation. An advantage is seen in the cleaner recovered fractions. During 1983 recovery of newspapers and magazines reached 52 percent. An estimated 200,000 tons were collected, out of an estimated recoverable portion of newspapers and magazines in Sweden's waste of 220,000 tons per year. About 90 percent of the population participates in wastepaper recovery (230 to 240 of 284 municipalities).[13]

2.2.2 Norway

About 40 percent of the waste entering a centralized separation plant in Oslo is reportedly processed into ferrous, paper, and plastic waste fractions, which are then recycled. This state-of-the-art facility went into full scale operation in 1985, processing household waste to paper, plastic chips, and ferrous metal for use in finished products. It also has the capability to compost grass, leaves and food waste.[10]

The recovered paper is fed to a small pulper, then to an additional pulping facility for marketing to a tissue manufacturer. The pulp, treated with hydrogen peroxide, would reportedly be acceptable in Norway for food packaging as well as for tissue and newsprint. The paper recovery program is in accord with Norway's virgin fiber conservation policy which limits the amount of forest products available for paper production.[14]

2.2.3 Germany[14]

Two notable features of German recycling efforts are a paper recycling policy and numerous agricultural composting plants located in rural areas. The government has a procurement policy favoring recycled paper, and even school supplies are required to have a rec cled paper content. In Baden-Wurttemburg, compost is used in vineyards, gardens, parks, and orchards. One environmental concern is the potential presence of heavy metal comtamination in the compost. Heavy metals have reportedly bioaccumulated in leaves of grape vines but not in the grapes themselves where compost was used as fertilizer. Despite these concerns, composting is expected to increase to 90,000 tons per year in Baden-Wurttemburg.

TABLE 2-2. SEPARATION AND UTILIZATION OF RECOVERED WASTES IN SWEDEN IN 1981 AND 1982
(In metric tons)

	Separated		Used or sold	
	1981	1982	1981	1982
Iron Scrap	4400	6800	200	1300
Plastic	2400	3900	0	30
Separated Fuel	37,000	75,800	4400	32,300
Compost	108,000	121,500	29,400	56,000

In addition, landfilling in Baden-Wurttemburg has been limited to 50 percent of total waste disposal capacity. Thus about 50 percent of MSW is managed by combinations of refuse recycling and refuse combustion. Currently in Bavaria landfills account for only 30 percent of waste disposal capacity, and, therefore, recycling and combustion are the major means of waste disposal.

Another feature noted in Germany's waste management included collection bins located at combustor sites in Wurzburg and Stuttgart for separation of hazardous items (batteries, aerosols, explosives) from waste before they enter the combustor. By removing these items plant operators hope to avoid damage to equipment and to minimize emissions of metals.

2.2.4 Denmark[14]

In Copenhagen labelled containers are available for disposal of segregated waste, e.g., yard waste, furniture, aerosol cans, etc. Also in Denmark, aluminum cans are not used for beverages, and beverage containers must be commercially reusable. Containers were reported to be used an average of 30 times compared to average usage of less than 10 times in U.S. markets. The return rate was estimated to be 99.6 percent.

Government procurement efforts have helped to create a strong market for recycled paper. Danish cardboard is more than 90 percent recycled and photocopy paper contains 45 percent recycled paper and straw. All available recovered ferrous scrap is recovered by the Danish steel industry, and discarded tires are being considered for use in highway asphalt. Also under investigation is the use of food waste from restaurants and institutions for processing into pet food. A plastics reprocessing plant is scheduled to open soon with a capacity of 25,000 tons per year for processing source separated plastic.

2.2.5 Italy

The city of Rome has several materials separation and recycling plants based on the Sorain-Cecchini process. These plants recycle about 65 percent of the waste (about 500,000 tons/year) they receive from Rome.[10,15] Paper, plastic, ferrous metal, and compost are recycled.

2.2.6 Japan

In 1983, about 67 percent of municipal solid waste collected in Japan was incinerated and the remainder was landfilled. The shortage of available landfill space has encouraged the practice of combustion which is expected to continue to increase. Also, strong emphasis has been placed on recycling and resource recovery (i.e., in the form of materials and/or energy) due to Japan's dependency on imported resources.[16] These objectives are being met through a combination of source separation programs and centralized processing facilities.[16,17]

Virtually all components of municipal solid waste are subject to recycling and/or resource recovery including: paper, glass, ferrous and nonferrous (i.e., aluminum) containers, plastic, and used electrical appliances. In 1984, Japan recycled more than 50 percent of the discarded newspaper as well as 81 percent of the discarded cardboard.[18] The Japanese government maintains a buffer stock of wastepaper to help stabilize the market.[19] By 1988, about 60 percent of returnable and nonreturnable glass beverage containers is expected to be manufactured from used glass cullet. Supply of glass cullet is enhanced by an approximate return rate of 95 percent of returnable beverage containers. Since 1977, Japan has operated a center where discarded electric appliances (e.g., televisions, refrigerators, and washing machines, etc.) are processed and separated into reusable components.[16] In general, Japan relies on non-profit organizations and volunteer groups to promote public awareness and to encourage public participation in recycling programs.

Centralized processing facilities play an important role in Japan's recycling and resource recovery objectives. Commercial processes have been implemented to sort mechanically and manually valuable recyclables from mixed refuse prior to combustion.[20] Recently, Japanese innovations have been demonstrated in pilot plants that produce methane gas from refuse by a high-rate methane fermentation process. In addition, usable fuel oil has been produced from paper and plastics by a pyrolysis oil recovery process.[21] These processes enhance resource recovery, are economical, and provide alternatives to the predominant waste disposal techniques: landfill and combustion. The Japanese government promotes these technological developments through financial and tax incentives.[16]

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3. SEPARATION METHODS

Two primary methods are used to separate recyclable materials from MSW: source separation and centralized processing. Source separation is accomplished when the waste generator (e.g., residential consumer, retail store, office building) sets aside recyclable wastes from other waste materials. Centralized processing separates recyclable waste from mixed municipal waste after it has been collected for disposal. This section describes how waste materials are recovered by these two methods and describes a few current programs in the United States and other countries that have successfully implemented recycling using these separation methods.

3.1 SOURCE SEPARATION

Materials most commonly recovered through source separation are used newspaper, glass, and aluminum cans from residential waste, used corrugated boxes from commercial waste, and high-grade office paper from office buildings. Source separation of other municipal waste components such as plastics, rubber, and organic materials is currently performed on a much smaller scale. Source separation methods in use for recovering recyclables from municipal waste (Table 3-1) are described in the following section.

3.1.1 Source Separation Methods

Source separation of residential waste components is primarily achieved through programs relying on curbside collection, neighborhood collection centers, or a combination of the two. Additional source separation of glass, aluminum, and in some cases, plastic containers is achieved as a result of container deposit laws.

An estimated 400-500 curbside recycling programs of varying sizes are operating in the United States.[1] Two successful programs are operating in San Jose, California and in Kitchener, Ontario (Canada). Both of these programs attribute their success in part to making attractive containers available in which residents can store recyclables and which are placed at the curb on pick-up days.[2,3] Neighborhood collection centers, while requiring less equipment, personnel and maintenance than curbside collection programs, generally achieve lower participation and lower volumes of materials.[4]

TABLE 3-1. SOURCE SEPARATION METHODS USED TO RECOVER RECYCLABLES FROM MUNICIPAL WASTE

Residential Waste		Commercial Waste	
Source Separation Methods	Materials Recovered[a]	Source Separation Technique	Materials Recovered
Curbside collection	Newspaper, glass, aluminum cans	Collection by waste dealers	Corrugated boxes, liquor and wine bottles
Voluntary drop-off centers	Newspaper, glass, aluminum cans	Employee recycling program	High-grade office waste, newspaper
Profit buy-back centers	Glass, metal cans, newspaper, magazines, corrugated boxes, plastics and wood		
Private/civic organization fund-raising drives	Newspaper		
Container deposit laws	Aluminum, glass, and plastic containers		
Home composting programs	Organics		

[a]Programs vary in types of materials recovered. Materials listed are typical.

Container deposit laws encourage consumers to separate and return used glass, aluminum, and plastic beverage containers by placing a returnable deposit on them. Such laws are currently in effect in Oregon, Maine, Massachusetts, Vermont, Delaware, Connecticut, New York, Michigan, and Iowa.[5,6]

Source separation of used corrugated boxes occurs primarily at retail stores, supermarkets, factories, and department stores. Waste paper dealers and recycling mills purchase waste from large generators of used corrugated boxes and arrange for its removal. The businesses generating corrugated waste typically operate compacting and baling equipment to reduce the volume of the waste for economical storage and transport. Recycling is also practiced by smaller businesses generating relatively small amounts of used corrugated boxes. Private individuals collect waste corrugated cardboard free of charge from these businesses and then sell it to waste paper dealers. About 40 percent of used corrugated cardboard is recycled in this manner in the United States.[6]

Paper recycling programs in offices are becoming increasingly common as a form of source separation, since an estimated 90 percent of office waste is waste paper. Office paper also is usually high grade. A recent survey of 12 unidentified office paper recycling programs sponsored by EPA indicated an average reduction in office waste of 34 percent, and, in one case, of 78 percent.[7] Offices with waste paper recycling programs request employees to separate recyclable waste paper in desk top or centrally located bins. The collected high-grade paper is then sold to a waste paper dealer who performs additional sorting and removal of contaminants, as necessary, and arranges for sale and transport of the waste paper to a recycling mill.

Current source separation practices also recover small quantities of plastics, rubber, and organics from municipal waste. Plastic soft drink containers are the only plastic waste currently recycled in significant quantities in the United States. The major mechanism for collecting these plastic containers is beverage container deposit legislation which requires consumers to pay a returnable deposit on all disposable beverage containers. Retailers collect the used containers and sell them to used plastic bottle processors, where the used containers are sorted, cleaned, and processed to remove contaminants (e.g., metal caps, labels) by a variety of manual and mechanical processes. Used plastic is currently used to make fiberfill and a variety of extruded products.[6] Some recycling centers provide facilities for individuals to dispose of tires.[8] Some communities encourage recycling of organic waste through composting. The communities operate facilities which accept and process organic waste into commercial compost to be used in landscaping and gardening. In addition, some communities have established programs providing materials and instructions for residents to perform their own composting.[2]

3.1.2 Source Separation Programs at Some Localities

Successful recycling programs involving source separation of residential and commercial waste have been implemented in numerous communities across the United States. Some of the most aggressive source separation programs have been implemented or are currently being implemented in large cities where development of alternatives to landfilling of municipal wastes has become a major issue. Examples of source separation programs in these cities are described below.

In New York City, the Department of Sanitation has recently implemented five pilot programs with the objective of increasing the level of source separation of residential wastes (i.e., newspaper, glass, and metal containers). These programs include: (1) a newspaper recycling program for high-rise apartment buildings; (2) establishment of "buy-back" centers in lower income neighborhoods that purchase glass, aluminum, bi-metal cans, tin cans, newspaper, magazines, corrugated paper, plastics, and wood from local residents; (3) curbside collection of newspaper, glass, and metal cans, in low-density neighborhoods; (4) establishment of a network of voluntary drop-off centers in Manhattan; and (5) containerized recycling program for materials other than newspapers in apartment buildings. Collectively, the City of New York estimates these residential source separation programs could result in a 5 percent reduction in the total municipal wastes generated, or about 1300 tons/day. The New York State Returnable Container Law could potentially recover an additional 5 percent of the residential waste in the form of glass, aluminum, and plastic beverage containers.[9]

The City of New York has also implemented programs to promote recycling of office waste paper. The City funds a private organization which provides technical assistance to offices interested in setting up office paper recycling programs. Further, the City recently expanded their city agency office waste paper recycling program with a resulting increase in tonnage of paper recycled. The City also sponsors waste paper recycling programs for non-profit organizations and a program with scrap paper dealers to promote desk-top recycling by their clients.[9]

In San Francisco, used newspaper is collected for recycling by community groups as fund-raising drives, by community nonprofit recycling centers, by for-profit buy-back recycling centers, and by garbage collectors. In addition, an apartment newspaper recycling program has recently been implemented. Other recyclables, including glass and aluminum cans, are also collected by voluntary drop-off and buy-back recycling centers. Residential curbside collection of recyclable materials was discontinued in San Francisco because of illegal scavenging and because it could never service more than about one-third of the population, due to San Francisco's unique demographics and topography.[10]

In addition to source separation programs for residential wastes, the City of San Francisco has implemented several programs to increase recycling of commercial wastes. The City collects wine and liquor bottles from bars and restaurants, separates corrugated boxes from mixed waste at the City's transfer station, and sponsors an office paper recycling program. This office program provides technical assistance and promotional materials to offices interested in establishing a paper recycling program. In addition, all city offices currently operate a waste paper recycling program. Recycling of waste wood and metals is performed at the City transfer station, and a composting program recycles animal waste at the City Zoo.[10] Altogether, the City estimates that about 22 percent of the residential and commercial waste generated by the community is recycled.[1]

3.2 CENTRALIZED PROCESSING

Virtually all of the post-consumer newspaper, glass, and aluminum recycled in the United States is recovered by the source separation methods described in Section 3.1. Yet only one-third or less of the total quantities of these discarded waste items are currently recycled by source separation methods.[11] Another method for recovering additional recyclables in municipal waste is by centralized processing of the mixed waste stream. Centralized processing to remove recyclables is practiced to a small degree at municipal waste transfer stations. It is also a key operation performed in conjunction with many waste-to-energy facilities, particularly those producing and firing RDF. Centralized processing techniques used to recover recyclable wastes from mixed waste (Table 3-2) are described in the following section.

3.2.1 Description of Centralized Processing Techniques

Transfer stations are operated by some communities to reduce transportation costs when convenient landfills are unavailable. To further reduce waste hauling costs, many transfer station operators selectively remove recyclables from the dumped waste. In particular, large metal appliances, white goods, auto parts, etc., are removed to prevent damage to compacting equipment. Used corrugated cardboard, newspaper, and wood may also be recovered from the mixed waste. These sorting operations generally are performed manually at the transfer station.[8,12]

Another example of centralized processing to remove recyclables from municipal waste is selective sorting of commercial office building waste. Instead of being combined with residential waste, commercial office building waste is routed to a processing plant where nonpaper waste is manually removed. This technique is practiced in at least one city (San Francisco).[10]

Resource recovery facilities recover the materials and energy value of municipal waste, thereby reducing the volume that has to be disposed in landfills by about 60 to 90 percent. Some of these facilities separate metals and other noncombustibles from the waste, and combust the remainder for fuel. Others process the mixed waste to maximize recovery of all recyclables including paper and plastics.

Two methods of separation are employed to remove recyclable waste fractions: front-end separation and back-end separation. Front-end separation removes recyclables before waste combustion. Back-end separation removes recyclables from the combustion ash or from mixed fractions recovered by front-end processing. Front and back-end separation techniques used to recover recyclable materials are described below. Some commercial processes using these techniques are described in Section 3.2.2.

TABLE 3-2. CENTRALIZED PROCESSING TECHNIQUES USED TO RECOVER RECYCLABLES FROM MUNICIPAL WASTE

Waste Type	Centralized Processing Techniques: Front-end separation (before incineration)	Centralized Processing Techniques: Back-end separation (after incineration)
Ferrous metals	Magnetic separation	Magnetic separation
Nonferrous metals (e.g., aluminum)	Jigging Water elutriation Heavy media separation Eddy-current separation Electrostatic separation	Jigging Electromagnetic separation
Glass	Jigging/screening Froth flotation Optical sorting Electrostatic separation	Jigging/screening Froth flotation
Paper	Manual sorting Air classification Electrostatic separation	None
Plastics	Air classification Electrostatic separation	None

3.2.1.1 Separation Techniques for Ferrous Metals.

Magnetic separation--Ferrous metals are effectively removed from raw refuse and combustor residue by magnetic separation. In front-end separation processes, paper and other sheet materials entrained with the ferrous fraction can be reduced with a multi-stage separator. The recovered ferrous fraction may be air classified to separate "tin" cans from heavy miscellaneous steel scrap. The tin cans must undergo a commercial detinning process before being recycled as scrap.[13]

Magnetic separation is also used to recover ferrous materials in combustor residue. In contrast to ferrous scrap recovered by front-end processes, ferrous recovered from back-end processes is cleaner having gone through the combustion process.[14]

3.2.1.2 Separation Techniques for Nonferrous Metals.

Jigging--Jigging is a wet process that separates materials of different specific gravities by pulsating water with a jig. Heavy particles settle on the screen and light particles are skimmed from the top. Jigging has been demonstrated to separate aluminum effectively from heavy nonferrous metals (zinc, lead, and tin) in raw refuse and to separate a glass and aluminum fraction from heavy nonferrous metals in combustor residue.[15]

Water elutriation--In the water elutriation technique, a controlled rising current of water is employed to create an effective, controllable specific gravity. Light material floats to the surface and overflows while heavy materials sink. This process has been used to process the air classified, heavy portion of raw refuse, separating wood, textiles, rubber, leather, and plastics from glass, aluminum, and other nonferrous metals. This process has also been used to recover a high-grade metal concentrate from scrap automobile shredder rejects (i.e., the nonmagnetic fraction from shredding junk autos).[15]

Heavy media separation--Heavy media separation utilizing fluids with specific gravities greater than 1 have been demonstrated to separate aluminum from heavy nonferrous metals in raw refuse and combustor residue. Commercial recovery of aluminum has been achieved with heavy media separation using suspensions of ferrosilicon, magnetite, or galena.[15]

Eddy-current separation--Eddy-current separation is a dry separation process based on the principle that an electromagnetic field passed through nonferrous metals induces eddy currents in the metals which interact (or counteract) with the magnetic field. These interactions exert a repelling force on the metals, separating them from the fields. Devices based on eddy-current separation have been demonstrated to recover a nonferrous metal fraction from raw refuse.[15]

Electrostatic separation--Electrostatic separation devices use an electrically grounded rotating drum and one or more electrodes. As feed materials enter the electrostatic field generated by the electrodes, the individual particles are charged. Conductors, including metal and paper, immediately lose their charge and are repelled by the grounded drum. Nonconductors, including glass, plastics, rubber, bone, wood, textiles and ceramics behave as nonconductors and remain pinned to the drum. This process has been demonstrated to recover aluminum and other nonferrous metals from municipal refuse.[15]

3.2.1.3 Separation Techniques for Glass.

Jigging/screening--Jigging separates glass and aluminum from nonferrous fractions in raw refuse and combustor residue. Glass is subsequently separated from aluminum by passing the mixture through a roll crusher which pulverizes the glass and flattens the aluminum, followed by screening to separate the two materials.[15]

Froth flotation--Froth flotation is a technique using differences in the chemical properties of finely ground glass and contaminants to achieve material separation. The glass and contaminants are mixed with a physicochemical reagent, which adsorb preferentially to the glass surface glass. The coated glass attaches to bubbles formed by agitating the mixture with air and is swept off the top. This process is generally performed in a series of froth flotation cells.[16]

Optical sorting--Optical sorting is a process designed to remove foreign materials from glass fractions and to separate glass by color. The process employs a series of photocells which separate the opaque particles from the transparent particles by matching the intensity of light transmitted through the particles with a fixed-shade background.[16]

3.2.1.4 Separation Techniques for Paper.

Manual sorting--Prior to shredding municipal waste for resource recovery processing, large items that could potentially damage the shredding equipment are removed. In conjunction with this step, sorting personnel may also be instructed to remove newspaper and corrugated boxes from the raw refuse. These materials are relatively easy to remove and may be sold directly to waste paper dealers.[13]

Air classification--After shredding, the first step in most materials recovery processes is to air classify the mixed waste into a lighter, mainly organic fraction and a heavier, mainly inorganic fraction. The light fraction consists primarily of paper and plastic. The heavy fraction may be further air classified to remove any remaining paper.[13]

Electrostatic separation--Electrostatic separation, as described previously, has been demonstrated to separate paper and plastic from air classification streams.[15]

3.2.2 Description of Commercial Centralized Processing Systems

3.2.2.1 Sorain-Cecchini System[17,18]--The Sorain-Cecchini system, developed about 20 years ago, automatically processes municipal waste into recyclable fractions (Figure 3-1). The system further upgrades these materials into marketable products, including aluminum and ferrous scrap, baled cardboard, polyethylene pellets, paper pulp, soil conditioner (i.e., compost) and ecological fuel. Fourteen plants using the Sorain-Cecchini process are under construction or operating presently worldwide. Locations include Italy, Brazil, Japan, Canada, Equador, Norway, Yugoslavia and Czechoslovakia. In addition, feasibility studies have been performed for construction of additional facilities using the Sorain-Cecchini process in the United States, England, Holland, Venezuela, Soviet Union, and numerous other countries. The Sorain-Cecchini system processes waste through a series of dry primary and secondary separating operations to segregate the following fractions: ferrous metals, aluminum, film plastic, organics, and densified refuse derived fuel (DRDF). The recovered organics fraction consists of hard plastics, organics, glass, ceramics, sand, and ashes. This system can also recover paper as cardboard and pulp. Also, the recovered organics fraction can be processed as animal feed, high grade compost, and low grade compost.

The incoming waste is sorted to remove over-sized pieces and waste that cannot be processed. The remaining waste is passed through a leveling device and a primary screen which separates the large fraction (nominal 8 in.), consisting mainly of paper, wood, and film plastic from the small, heavier fraction, consisting mainly of organics, glass, ceramics, metal, sand, and ashes.

Both the large and small fractions from the primary screen undergo a series of classification steps, each producing a light and heavy fraction. These fractions are further processed into like fractions and distributed to recover lines where materials are processed into a marketable form.

Ferrous metals are recovered by magnetic separation at three points in the waste recovery process. The recovered ferrous fractions are fed to a specially designed hammermill which cleans the ferrous fraction through friction and densifies it through compression. A final magnetic separator separates the ferrous metals from the nonmetals loosened by the hammermill. Following ferrous recovery, the heavy fractions are processed by eddy current separation to recover aluminum. The aluminum fraction is crushed to densify the material and to reduce voids.

Paper is separated by a series of air classification steps from plastic and other heavier materials and is either processed into DRDF or paper pulp. After densification, the DRDF is sold or used as fuel on-site. The recovered plastics fraction is shredded, washed, dried, and processed into pellets.

Organic fractions, consisting of small organics, glass, ceramics, sand, ashes, hard plastic, small pieces of wood, and some of the smaller heavier materials which are otherwise being recovered, are separated at several points in the waste recovery process. These fractions are processed into a raw compost in an aerobic digestor and then cleaned to remove inorganic materials. The remaining organics fraction may be further processed to make animal feed or commercial compost.

3.2.2.2 Stardust '80[19] Stardust '80 is a comprehensive, multi-purpose resource recovery system developed by the Japanese government. The system features processes for sorting mixed waste into components from which compost, pulp, fuel gas and oil, and light-weight aggregate may be recovered. The system is currently in operation in Tokyo and Yokohama.

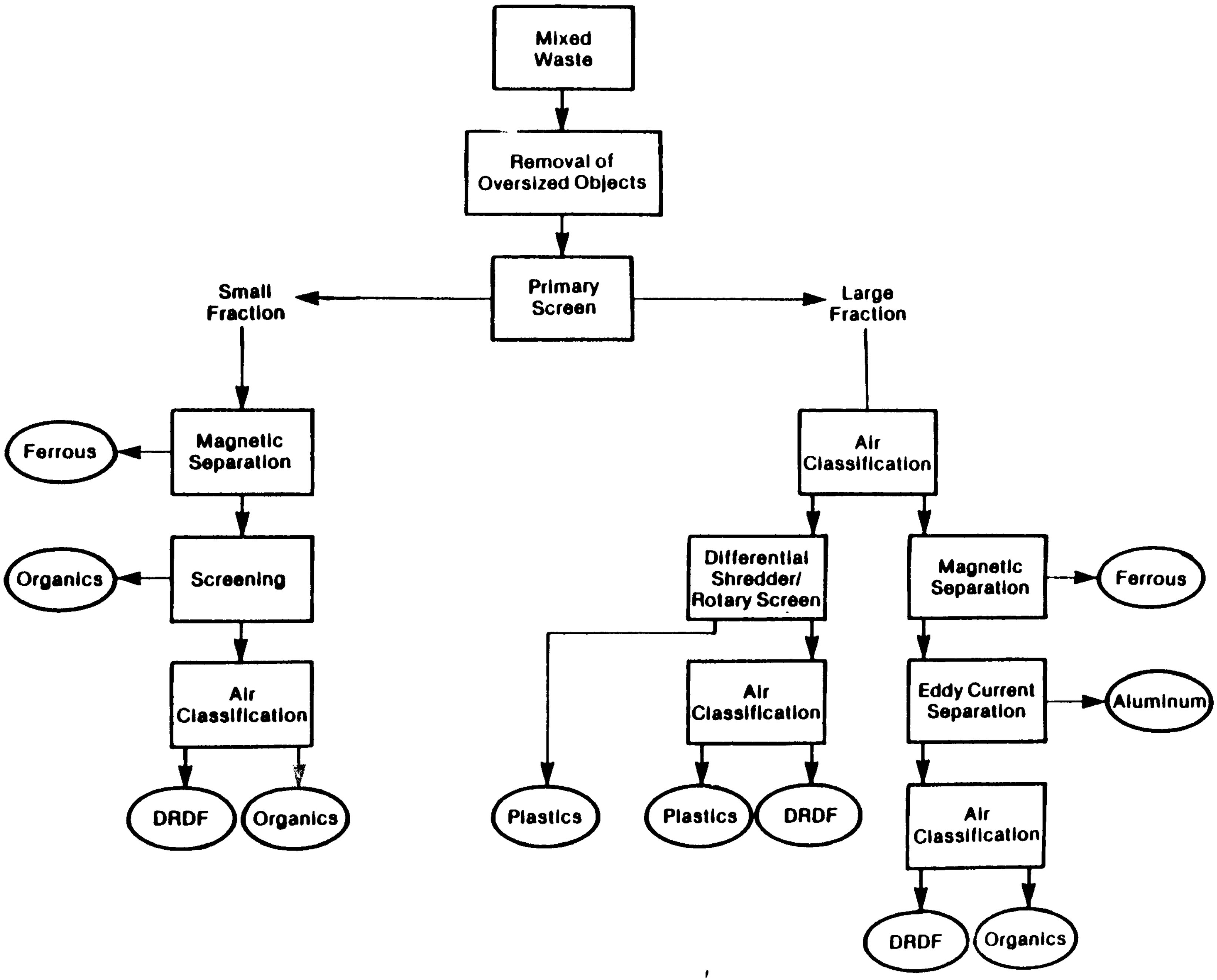

Figure 3-1. Separation Steps in Sorain - Cecchini Process

At the Yokohama plant, incoming refuse is separated by a semi-wet pulverizing classifier into three primary fractions: garbage, paper, and plastics. Before 1981, the garbage fraction underwent further processing to separate glass and dirt, before being converted to refined compost by a high rate composting system. The glass and dirt removed was subsequently processed into light-weight aggregate. The paper fraction was air assified and then further processed to recover refined pulp. The plastics fraction was passed through a magnetic separator to recover ferrous metal, shredded and then processed into fuel gas (heating value - 620 Btu/scf) by a two-bed pyrolizer. In 1981, a high rate fermentation system was added to convert the garbage fraction into methane with a heating value of 650 Btu/scf.

At the Tokyo plant, only the paper and plastics fractions separated from incoming refuse are further processed on-site. The paper-plastics fraction recovered at the Tokyo plant is processed through a fluidized bed pyrolysis oil recovery system into fuel oil having a heating value of 14,400 Btu/lb and a solid fuel with a heating value of 6,660 Btu/lb.

Developers of the system emphasize that different combinations of the recovery processes demonstrated at the Yokohama and Tokyo plants may be used at other locations depending on site-specific needs. For example, the composting process is recommended for facilities in cities with large populations where refuse typically has a higher proportion of garbage. Garbage is more difficult to incinerate than other refuse types. Likewise, methane fermentation systems are recommended when municipal waste and sewage treatment efforts can be combined. A flow diagram (Figure 2) illustrates the basic recovery process operations offered by the Stardust '80 system.

3.2.2.3 <u>ORFA Process</u>[20] A recent development in centralized waste processing is the ORFA process. A prototype facility utilizing this process has been operating in Switzerland for the past 3 years. Plans are currently underway to construct commercial facilities based on the ORFA process in the United States. The ORFA process converts municipal refuse into three marketable fractions. The first fraction, ORFA fiber, is a sanitized and stabilized fibrous material composed mainly of cellulose. Its expected uses include feedstock for agricultural products and pulp and paper, and in energy

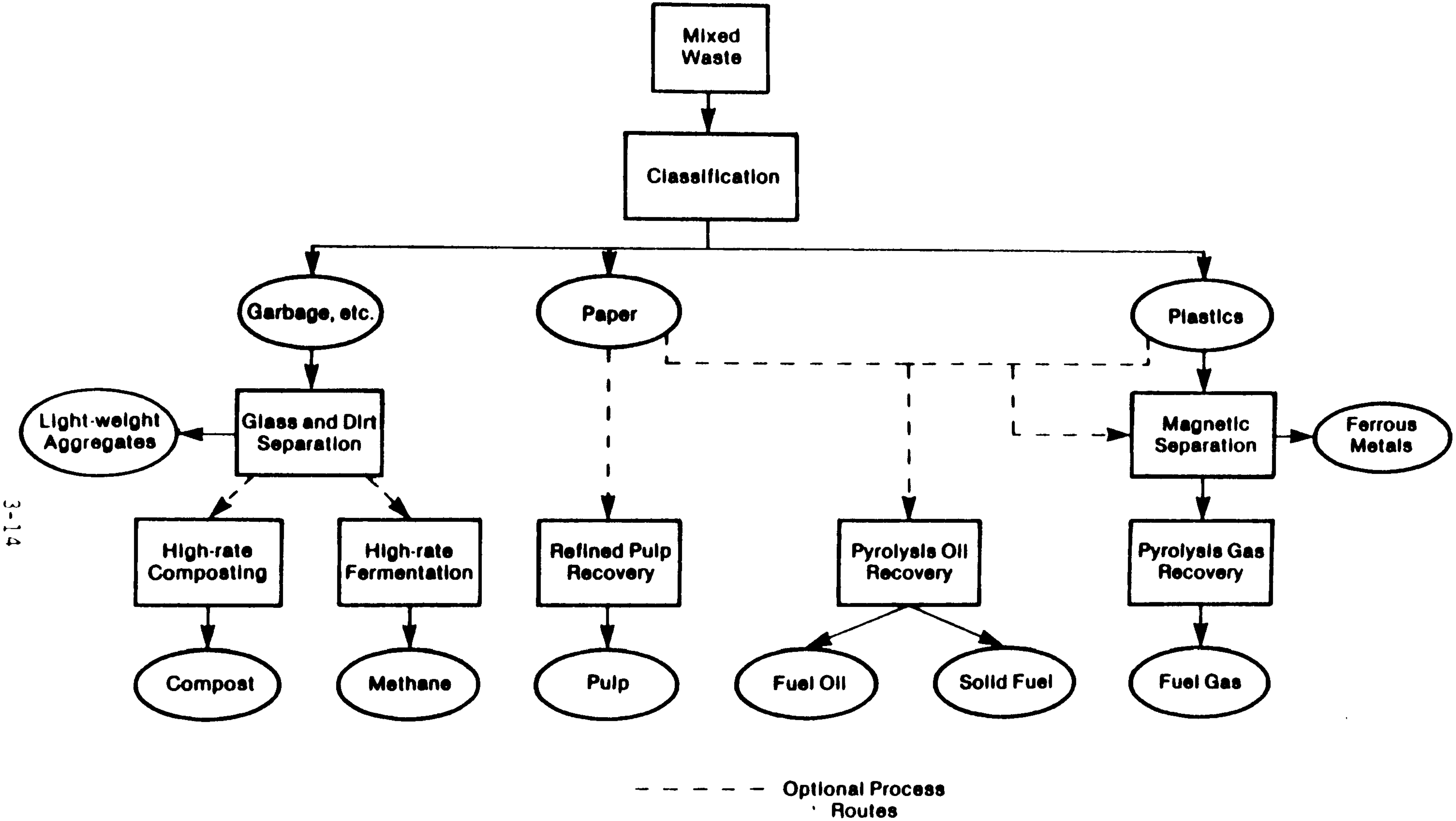

Figure 3-2. Optional Recovery Processes Available in Stardust 80 System

and building materials industries. The second fraction, Granulite, is a composite of plastics, glass, nonferrous metals, sand, dust, grit, and other heavy materials, and is intended for use in building materials and road repair applications. The third fraction, a ferrous metal fraction, is shredded for sale to scrap metal dealers. The primary recovery steps in the ORFA process include size reduction and ferrous metal removal followed by drying, stabilization, and sanitization by ozone. The remaining processed waste is then separated into ORFA fiber and Granulite by a series of size and density classification steps. To reduce odorous emissions from the various process steps, exhaust gases are vented to a bio-filter which traps odorants and neutralizes them by aerobic digestion.

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4. MATERIALS AND MARKETS

This section presents information on the separation feasibility and marketability of individual municipal waste constituents. The municipal waste components covered in this section include: aluminum, ferrous metals, glass, paper, plastics, wood, rubber and organics. Techniques currently used or under development to separate each of these components from municipal waste for recycling are identified. Current and potential markets for recovered materials in the United States are described.

4.1 ALUMINUM

Aluminum recycling in the United States has been very successful. In fact, it has been so successful that Reynolds Metals found it advantageous to solicit recycled aluminum in the United States rather than continue alumina and bauxite production overseas. A further indication of aluminum recycling's success is found in U.S. Bureau of Mines statistics showing 32 percent of U.S. consumption of aluminum in 1982 was recycled aluminum.[1]

In 1984, approximately 1.5 million tons of aluminum was discarded with municipal waste. Although steadily increasing, the tonnage of aluminum discarded is small. About 643,000 tons of aluminum were recovered in 1984 from discarded containers and packaging. The recovered aluminum containers were then used to make sheet for new cans. Recovery of aluminum waste is expected to continue to grow slowly with the increased demand for aluminum cans. The percent recovery is expected to stabilize at about 50 percent of the cans in the total municipal waste stream.[2] The amount of aluminum recycled may have little effect on landfill space, but revenues generated from the sale of aluminum waste are high and help to offset other waste handling and recycling costs.[3]

Source separation has been a major method of separation of aluminum cans and packaging from the municipal waste stream. In addition, several separation processes for recovering aluminum scrap from mixed refuse have been described.[4] Eddy current separation has demonstrated 70 to 80 percent recovery of aluminum from mixed refuse.[4,5]

4.2 FERROUS METALS

Discarded ferrous metals totalled about 11 million tons in 1984. Of the 11 million tons, about 2.9 million is estimated to be steel packaging (cans, pails, buckets, drums). Steel once accounted for all beverage cans but has been largely supplanted by aluminum. The percent decline in the proportion of ferrous materials in municipal waste is expected to continue.[2]

Ferrous metals are easily removed magnetically from mixed municipal waste. Centralized separation processes typically include an operation for separating shredded ferrous scrap. Combustion operations may separate ferrous materials before combustion or after combustion, when the metal has been sterilized. Even though ferrous scrap is one of the easily separated constituents c mixed refuse stream, it is not an intensively recycled part of municipal refuse. Franklin Associates[2] reports a continuing decline in quantities recycled, because other sources of high quality ferrous scrap are available to secondary ferrous metal producers. This, coupled with declining demand for steel, means that ferrous scrap recovered from municipal waste is marginal in the marketplace.

One of the major technical problems associated with recycling steel packaging can be overcome through detinning processes that remove tin from the scrap, thereby producing a high quality scrap and increasing its utility for use by secondary metals producers.[6,7] An optimum scheme for recovery of ferrous materials is the separation of steel cans from unburned refuse after shredding, followed by detinning to recover the tin.[8] The scrap can then be further shredded or compacted to make a premium scrap.

While the market for shredded ferrous scrap recovered from municipal waste does not look favorable nationally, local market conditions may make recovery economically feasible. Location of municipal waste recovery facilities near detinning or copper mining operations may capitalize on good local market potential. For example, New York City, in developing its recycling strategy, found one market for steel cans in the local area - a detinning facility in New Jersey.[9] The largest use of recycled tin cans is in refining copper ore. For ores rich in oxides, a leaching process based on a copper-iron ion exchange is used with cans as a source of iron. The demand for cans to be used in this process is localized in Arizona and Utah.[10]

4.3 GLASS

Glass accounted for an estimated 14 million tons of waste generated in the United States in 1984, or about 9 percent by weight of the total municipal solid waste generated. The proportion of glass in the waste stream peaked in the early 1980's at 11 percent. Over the past 5 years, glass containers have lost considerable market share to aluminum and plastic containers. The trend is expected to continue and by the year 2000, the percentage of glass in the waste stream is projected to fall below 8 percent.[2]

In 1984, about 1.0 million tons of glass was recovered for reuse. Virtually all of the recovered glass was in the form of glass containers (i.e., beer and soft drink containers, wine and liquor bottles, food bottles and jars, etc.). The primary market for recycled glass containers is the glass container manufacturing industry. Glass manufacturers can replace at least 50 percent of their raw materials with cullet derived from recycled glass containers and from scrap cullet (i.e., in-house scrap or scrap purchased from bottling plants). However, to be suitable for use by the glass manufacturing industry, cullet from recycled glass containers must be separated by color (i.e., clear, amber, and green) and be relatively free of contaminants such as paper, plastic, metals, and rocks. Strict quality specifications are maintained by the glass manufacturing industry for recycled cullet.[11,12] For these reasons, and because raw materials for making glass are relatively inexpensive, most glass manufacturers use no more than 20 percent cullet in their glass batches.[13]

Other markets for recycled glass which have less stringent quality requirements include manufacturers of glass wool and certain building and paving materials.[14,15] Many of these markets can accept mixed-color cullet with relatively high levels of contaminants. Consumption of recycled glass by these markets, however, is minimal at present. Efforts to develop more fully these and other markets for used glass by experimental production and testing of materials made from recycled glass are being undertaken by the Bureau of Mines.[15]

Glass containers are recovered for reuse in three ways: source separation, mechanical separation, and reuse programs. Source separation accounts for the majority of recovered glass containers.[13] Some processing is typically required to sort the collected bottles by color and to remove contaminants before the recovered glass can be turned into cullet for reuse by the glass industry. These processing steps have traditionally been performed manually. Recently, mechanical processes have been developed to process "dirty" glass.[16] Also, processes relying on optical sorting of mixed-color glass into single-color glass fractions have been demonstrated.[13,15] In general, though, processing of glass into clean, single-color components is likely to continue to be a labor-intensive process.

Mechanical separation of glass from mixed municipal waste for purposes of resource recovery, or to enhance the fuel quality of the residual waste, is practiced by a number of facilities. The glass fraction recovered by these processes is generally not suitable for use by the glass container manufacturing industry because it is mixed-color and has a relatively high level of contaminants.[12] Instead, the recovered glass fraction may be used in production of various building materials, as an aggregate in paving and construction projects, or as landfill.[15,17,18] Mechanical separation of glass usually is achieved by a series of classification and separation steps to form a glass-rich fraction which is then subjected to froth flotation to concentrate the glass further.[13,19]

Reuse programs rely primarily on container deposit legislation requiring consumers to pay a deposit on beverage containers which is redeemed when the containers are returned to the retailer. Nine states have passed returnable container deposit laws (Section 3.1.1). An additional twenty-three states reportedly are considering similar legislation.[20] Bottles collected as a result of these laws have the advantage of being easily color-separated by redemption centers, thereby facilitating their processing for reuse by the glass container manufacturing industry. The impact of container deposit laws on overall recycling efforts is uncertain. Although these laws have been effective in diverting up to 90 percent of discarded glass containers from municipal waste, they have resulted in consumers switching to containers that are more convenient to handle (e.g., plastic and aluminum).[21] Further, they have created flooded markets for some types of glass cullet.[22] In New York City, for example, availability of green cullet primarily from imported beer bottles has increased significantly and exceeds current market demand for green glass. In general, the increased availability of glass cullet from container deposit laws tends to drive down the price for green and amber cullet but has little effect on ear (i.e., flint) cullet.[9] The net result is that privately owned recycling businesses which are no longer able to collect d process glass (and aluminum) containers profitably may decline, thus reducing recycling efforts for other materials.[21]

4.4 PAPER

Waste paper and paperboard is the single largest component of municipal waste, accounting for an estimated 37 percent by weight of total municipal waste generated in 1984.[2] Of the approximately 62.3 million tons of paper and paperboard waste generated in 1984, an estimated 13 million tons, or 21 percent, was recovered for reuse. Both the total amount of waste paper generated and the amount recycled are expected to increase slowly over the next few years.[2]

Most of the recovered paper and paperboard in the United States is reused by the paper and paperboard manufacturing industry. Of the 600 paper and paperboard mills in the United States, 200 depend exclusively on waste paper for raw material and another 300 mills use a percentage of waste paper as their raw material.[23] To make use of recycled fiber, paper and paperboard mills require special equipment and facilities to perform pulping, cleaning, screening, and refining operations needed to prepare recycled fiber-stock.[24] Before recovered waste paper can be used by the paper industry, steps must be taken to remove contaminants introduced during production and fabrication of paper products or during the use of those products. Example of contaminants introduced during production and fabrication include: non-emulsifiable latexes; plastics laminated to paper; wet strength resins; nondeinkable inks, hot metals in bindings; waxes, resins and other polymers for special products; chemical additives; pressure sensitive tapes for sealing; heat seal labels;

and some paper coatings. Dirt, food, metal, rags, wire, glass, and plastics are examples of waste paper contaminants introduced during use.[25,26] The ability to use various grades of waste paper to replace virgin raw materials depends on the type of paper being manufactured. For example, mills that produce business printing and tissue paper can utilize only the highest quality grades of waste paper. Examples of these include scrap from paper-converting plants and data processing centers, ledger paper from offices, and printed bleached paper that has been processed at a deinking mill. Bulk grades of waste paper, including recycled newspaper, corrugated boxes, and mixed office waste paper, are used by mills that make newsprint, paper board, and construction paper.[9]

Source separation is the most prevalent method of recovery of waste paper for reuse by paper and paperboard mills. Most notably, source separation is used to recover newspaper, corrugated boxes, and high grade office paper. Newspaper is particularly well suited for recycling because a competitive market for used newspaper exists and because it comprises a significant enough portion of the municipal waste stream to afford appreciable landfill savings when recycled.[22] Approximately 3.3 million tons of newspaper was recycled in 1984 corresponding to abou- 24 percent of the discarded newspapers.[2] Newspaper collected by residential source separation programs is typically sold to a waste paper dealer who processes the paper by removing contaminants and densifying for bulk resale to paper mills.[9] Major markets for used newspaper are mills producing boxboard or newsprint and producers of specialized construction and building materials.[25,26]

Used corrugated boxes are the largest single source of waste paper for recycling.[25] In 1984, an estimated 6.8 million tons, or about 36 percent, of used corrugated boxes were recycled.[2] As with paper dealers handling used newspaper, used corrugated cardboard dealers manually remove contaminants from the recovered corrugated boxes and perform any additional processing required by paper mills purchasing the used corrugated paper. Major markets for used corrugated boxes are paperboard mills and producers of specialized construction and building materials.[9,26]

Current programs to recycle high grade office paper are motivated by the relatively high value of these materials in the waste paper market. Dealers typically pay more for high grade office paper than for bulk grades of waste paper, such as newspaper and used corrugated boxes, because of the capabi..ty of paper mills to use the waste paper as a direct substitute for wood pulp in the papermaking process.[9] Recycling programs have been established in a growing number of office buildings to recover the value of their high grade waste paper. In 1984, about 800,000 tons (16 percent) of high grade office paper waste were recycled.[2]

Waste paper recovered mechanically from mixed municipal waste generally does not meet industry specifications for use by paper mills in the United States, although some paper mills have indicated their willingness to use waste corrugated boxes and mixed paper recovered from mixed waste that is predominantly commercial or office waste.[26] However, in most cases, the paper industry would require waste paper recovered from a mixed waste stream to undergo extensive cleaning and sterilization before it could be used to make even low-grade paperboard.[15] Other markets with less stringent quality requirements for recovered waste paper from mixed waste streams include manufacturers of cellulose insulation, packing and cushioning materials, and building products.[23] These markets can accept the lowest grades of waste paper and are an outlet for otherwise unusable paper fiber.[26] Although consumption of waste paper by these markets at present is limited, development of these and other markets for mixed waste paper is considered an important factor toward increasing significantly the amounts of waste paper that can be economically recycled and reused in the future.[27]

Most of the waste paper recovered in the United States is consumed in U.S. paper mills. In 1984, however, an estimated 3.4 million tons of waste paper was exported for use as raw material in foreign paper mills.[23] Estimates of future exports of waste paper are favorable in light of projected shortages of indigenous forest resources in Europe, Japan, and other parts of Asia. Cities like New York City are depending on the expansion of foreign markets to help absorb the waste paper collected under their comprehensive recycling programs.[9]

4.5 PLASTICS

Approximately 9.7 million tons of plastic waste was generated in the United States in 1984, representing about 6.5 percent by weight of the total generated municipal waste. Of the total plastic wastes generated, plastic containers and packaging make up the largest fraction, accounting for over half of plastic discards in 1984. The amount of plastic waste discarded annually has more than doubled since 1960 and, while still a small fraction, plastics is currently the most rapidly growing material in the solid waste stream. By the year 2000, discarded plastic containers and packaging alone are projected to represent more than 5 percent by weight of the total waste stream.[2]

Recycling of post-consumer plastic waste is currently not a common practice. In 1984, less than 100,000 tons of post-consumer plastic was estimated to be recycled.[2] However, one type of plastic waste is currently the focus of a limited but successful recycling effort. Polyethylene terephthalate (PET), most commonly used in 2-liter soft drink containers, is currently being recovered and reused in a variety of applications. In 1984, an estimated 63,000 tons of PET containers, or about 18 percent of the total PET containers discarded, was recycled. The primary source of PET containers for recycling was states with container deposit laws.[2] The principal market for recycled PET is polyester fiber staple, used in clothing, pillows or other items, or for glass-fiber products. Plastic strapping for pallet wrapping is another use for recycled PET, but this market is small (5 to 18 million pounds per year).[28] Methods are also under development to convert PET to polyols for use in rigid or flexible urethane foams.

The FDA regulations for food packaging materials preclude reuse of recycled PET to make new soft-drink containers.[1,20] Different processes are used by intermediate dealers to process soft-drink containers for PET recycle. These containers typically contain several components in addition to PET, including a high-density polyethylene (HDPE) base cup, paper or paint labels, and an aluminum and/or plastic cap. Some processors separate these materials by first removing the cap and base cup (manually or mechanically), grinding the remaining material, and then washing the ground PET to remove paper and adhesive. Another system first grinds the whole bottles and then passes the ground materials through an air classifier to remove paper, an electrostatic precipitator to remove aluminum, and a flotation system to separate plastic resins. Both methods are reported to be capable of supplying high purity PET.[20] Also, the recovered HDPE may be sold to plastic scrap users for production of flower pots, plastic tubing and other products as well as for the manufacture of new base cups.[29] Recycling of PET containers is expected to continue to increase as additional states pass container deposit laws, and as additional uses for recycled PET are identified.

Several factors contribute to the overall low level of post-consumer plastics recycling. Technologies for removal of contaminants in the form of metal, paper, wood, ceramic, and other substances which have been integrated into plastic products have been slow to develop.[9,30,31] Further, to recycle more post-consumer plastic wastes, the majority of which consist of multiple resins, further technological development is needed for processes that segregate plastic resins into homogeneous groupings or for end uses which can utilize mixed resin scrap. Processes that separate mixed plastic wastes into recyclable fractions or that use mixed resin scrap for manufacturing new plastic products are practiced on a limited scale at present.[9,31] For example, the Sorain-Cecchini process described in Section 3.2.2 is capable of separating and recovering so-called film plastic (i.e., low density polyethylene) from other plastic waste by a series of air classification steps. The recovered film plastic is either baled and sold to the injection and compression molding plastic industry or formed into pellets and combined with 5 to 10 percent of virgin materials to make new film plastic. The remaining plastic wastes (i.e., PVC, PET) are not currently salvaged by this process, but some could be recovered through source separation.[32]

One suggestion for improving the ability to recycle plastic products is to require manufacturers to label clearly plastic products so that the consumer could identify easily the type(s) of resin contained in the plastic product. This would facilitate recycling of plastic waste by source separation because the consumer would be able to segregate plastic waste into single-resin components.[33]

Emphasis has also been placed on developing techniques for processing recovered mixed plastic waste into a reusable form. One process in use is the Reverzer process, developed by Mitsubishi Petrochemical in Japan, which utilizes mixed thermoplastic wastes with up to 20 percent non-thermoplastic materials (e.g., paper) to make extruded and molded plastics products with thick cross sections. These products include fence stakes, irrigation pipe, pallets, part benches, road drains, cable drums and building panels. At least 30 companies worldwide reportedly are using this technology to make plastic products. Other processes include: (1) the Japan Synthetic Paper process which compression molds film scrap (from mixed plastics) with wood chips to make chip/wall board, and (2) the Regal Packaging process which first granulates mixed plastic wastes and then fuses the granules with heat into sheets used in compression molding to produce a variety of plastic products. The latter technology is reportedly capable of handling plastics with paper, metal, glass, and sand contamination.[31]

4.6 WOOD

Discarded wood wastes comprised to about 5.1 million tons in 1984. Wood waste removed from the waste stream reportedly has been sold as wood chips for firing boilers.[34] Waste wood recovered from refuse also has been used to make paper pulp.[34,35]

In San Francisco, wood is reported to be separated by hand from construction delivery boxes. After the wood passes through a hammer mill and grinder, the wood chips are sold for boiler fuel. Tree branches from city parks and from tree pruning companies are also processed in this way by two companies that began work in 1984. Recycling wood from construction waste in this manner results in a significant reduction in wood waste to be landfilled and is reported to be a lower cost alternative to landfilling.[36]

4.7 RUBBER

Gross discards of rubber products in 1984 comprised 1.9 million tons, of which 1.2 million tons were tires and tire products. Tonnage of discarded rubber tires has been declining with decreasing car sales and the advent of smaller and more durable tires. Small growth in discards is anticipated as car sales increase with the increase in number of people of driving age.[2] Recovery of tires for reuse or recycling accounted for 5.2 percent of discards in 1984, down from 20 percent in 1960. Thirty-three thousand tons of tires was retread in 1984, and rubber recovery for other uses amounted to 103,000 tons.[2]

Recycling options for rubber tires include retreading and rubberized asphalt.[37] Rubber asphalt mixtures have been demonstrated in Arizona to extend substantially pavement life and reduce the amount of resurfacing required.[42] The Danish government is reportedly considering using discarded tires in highway asphalt[38], as is the city of New York.[9] However, analysts have not seen an optimistic future for recycling rubber products.[2,37]

Tire disposal presents problems because landfilling is an inefficient use of landfill space, and tires are non-biodegradable. Air trapped in tire rims causes the tires to rise to the surface. Burning tires in regular combustion equipment can cause high levels of sulfur emissions and black, sooty-laden smoke. Many old tires are stacked outdoors where they can harbor rodents and insects.[43] Shredding is one procedure that can reduce the volume required in landfilling. New York City is currently using shredded tires as a part of their daily landfill cover.[40] Combustion of shredded rubber or whole tires in specially designed equipment as a cheap energy source is receiving attention as a disposal method, thus reducing required landfill space and recovering energy.[16,37]

4.8 COMPOST

Quantities of disposed yard waste are poorly documented and vary widely across the United States. Disposed yard waste was estimated in 1984 to be 23.8 million tons. Some yard waste is composted but the quantity is not known and is expected to be small compared to the total waste stream.[2]

There are reportedly numerous composting facilities in rural Germany.[38] Markets for compost exist in Rhineland vineyards, gardens, parks, and orchards. In the United States, the city of San Francisco has established production of compost from zoo animal bedding and manure. The composted materials is marketed commercially as "Zoo Doo." San Francisco is also reportedly planning composting for tree trimmings, leaf litter, and grass clippings from Golden Gate Park for use on city parks and golf courses.[36]

In New York City, low grade compost is being used as landfill cover. This measure is a volume reduction measure because cover material consumes about 70 percent of available landfill volume.[39] Compost is also being produced in Berkeley, California in a centralized city compost facility.[41]

Producing a refuse material for composting requires several processing steps aimed at reducing the size of the refuse components and separating compostable materials from other materials. One recommended system includes the following steps: 1) shredding, 2) magnetic separation of ferrous materials, 3) air classification to remove a large portion of heavy inorganics, and 4) screening to removal grit, glass, and small hard particles.[44]

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5. EFFECTS OF RECYCLING ON COMBUSTION

Because recycling is not expected to completely eliminate the need for combustion, it is necessary to consider the effects of removal of recycled materials on waste combustion. Test results show that combustion can reduce the volume of waste by 60 to 90 percent.[1] If a portion of the waste can be removed and recycled prior to combustion, however, a 100 percent volume reduction is possible. Therefore, the goal in both methods of waste management is reducing landfill space required for waste disposal.

Waste constituents recycling can reduce combustion costs in three ways. First, less combustion capacity is needed and smaller equipment usually decrease construction costs. Second, combustor residue is decreased when glass and metals are removed, thus lowering operating costs and tipping fees[a]. Finally, maintenance cost savings may be realized if abrasive waste components such as glass, metal and grit are removed.[2]

Two types of effects of recycling on combustion will be considered briefly in this section: 1) effects of materials removal on the combustion process and 2) effects of materials removal on emissions from combustion. Much of this section is based on logic and supposition. Little data were found to determine what effect intensified recycling will have on refuse combustion.

5.1 EFFECTS OF RECYCLING ON THE COMBUSTION PROCESS

When considering the effects of materials removal from the municipal waste stream available for combustion, it is useful to identify two categories of waste constituents, combustible and non-combustible, because the combustion process acts only on the combustible portion to effect a volume reduction. The non-combustible portion may also be changed chemically and physically by the process and may affect the operation, but it is not actually combusted.

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[a]Tipping fees are the fees charged by a waste handling facility to accept waste.

It appears logical that removal of non-combustibles would not adversely affect the combustion process. Removal of significant quantities of metals, glass and grit should, in fact, decrease slagging and clinker[b] formation through removal of substances that form slag and clinkers. Decreased slagging and clinker formation should then, in turn, improve combustor on time availability and improve overall combustor operations and performance.

Few data were found that could be used to affirm or deny this logic. Data concerning combustion of processed waste such as RDF to unprocessed waste are largely noncomparable because of differing combustor designs. However, a series of tests run at a rotary combustor designed for mass firing was performed to determine what effects non-combustibles removal has on energy recovery from refuse.[3] The tests showed removal of glass, grit, and metals resulted in reduced clinker formation and slagging and improved combustor availability of up to 40 percent; long-term availability was increased by 20 percent. The comparative tests of processed versus non-processed fuel also showed improved feed and ash handling, and steam generation rates were higher and more consistent.

These few data would tend to support the logical deduction that removal of non-combustibles from refuse may improve combustor performance. Other benefits, as mentioned previously, include improved equipment life and the ability to use smaller combustion equipment due to processing smaller quantities of waste. Also, the removal of noncombustibles would tend to increase the heating value of the waste, and therefore allow more efficient combustion.[2]

Removal of combustibles, on the other hand, would remove constituents that support combustion, mostly paper. (Note: Yard waste is also combustible, but is associated with so much moisture that combustion is poorly sustained. Therefore, removal of yard waste or other wet organic waste would not generally be considered detrimental to the combustion process.) It appears that recycling efforts might compete for the fractions of the refuse needed by the combustion process to reduce the volume of the remaining waste. For, if

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[b] Slag is rock-like mineral material formed by the melting and subsequent solidification of ash in a furnace. A clinker is a large solidified mass of slag material.

a heat content high enough to sustain combustion is not maintained, the addition of fossil fuel may be required to carry out the combustion process. Addition of fuel would increase the cost of combustion.

According to Franklin Associates, municipal waste discarded nationwide in 1984 was composed of 37 percent paper and paperboard and 7 percent plastic after current recycling.[4] Assuming the paper fraction has a higher heating value (HHV) of 7,925 Btu/lb and the plastics fraction has a HHV of 11,708 Btu/lb and assuming the total w -te has a higher heating value of 4,500 Btu/lb, it can be seen that in excess of 80 percent of the heating value may be found in the plastics and paper in the waste available for combustion, with most of it in the paper fraction.

Based on the previous discussion, paper is the combustible component which would be most likely removed for recycling in the near future. For purposes of combustion, paper is an important constituent in the waste. It is estimated that about half of the wastepaper generated each year in the United States is not recyclable, either because the paper is too contaminated, having been used in some way that precluded its recovery from the refuse stream, or because it is uneconomical to collect. Even so, removal of half the paper (using national average figures) and holding everything else constant, would reduce the HHV of the waste to about 3750 Btu/lb, a reduction in heating value of 17 percent. The value of 3750 Btu/lb is about the lower limit of the value required to sustain and complete combustion for current combustor designs. Though this heating value would likely still be sufficient to support combustion, it may not be high enough to allow combustion practices that minimize organic emissions to be achieved. Therefore, combustion of a low heating value waste would probably require the addition of supplemental fuel to meet guideline requirements.

Though removal of some combustibles may adversely affect combustion, refuse and local market conditions are highly variable, and the effects of removing paper or other combustibles from waste that is to be incinerated has to be considered on the local level. The fact that recycling programs also may include removal of noncombustibles must also be considered. For example, in plans for solid waste management, Essex County in New Jersey analyzed the effects of a planned materials recovery program on a planned combustor.[5] Essex County's analysis showed that in that particular situation, using specific Essex County waste characteristics, materials recovery was actually predicted to increase the higher heating value of the waste, even with almost complete removal of paper. Essex County found that the effects of removal of paper tended to be offset by the removal of glass and metals which have no heating value. Similar situations might be anticipated where RDF is being produced for combustion, if recycling of paper is extensive before the waste reaches the waste-to-energy facility.

The effects of recycling on the fuel value of incinerated waste have been addressed by one major manufacturer of waste combustion equipment, Signal Environmental Systems, Inc. According to this manufacturer, an all-encompassing recycling program removing both combustibles and non-combustibles should not appreciably alter the fuel value of the incoming waste. Under such conditions, the removal of non-combustibles (i.e., glass, metal cans, etc.) would have no effect on thermal efficiency, and on a per-ton basis, enough paper should remain after recycling to maintain present levels of electricity and steam production with no requirement for auxiliary fuel. One study estimated that a newspaper recycling program achieving 25 percent participation would reduce the fuel value of the remaining waste by only 2.8 percent.[2]

5.2 EFFECTS OF RECYCLING ON EMISSIONS FROM COMBUSTION

Removal of non-combustibles from the refuse through recycling should cause no increase in emissions to the atmosphere from combustion. Logically, it would seem that removal of non-combustibles from the feed to the combustor would decrease ash quantities to be disposed and particulate emissions. Also, if the removal of metals and glass improves combustion conditions (Section 5.1), lower emissions of carbon monoxide and organic compounds would be predicted. Results of tests at the previously mentioned Gallatin, Tennessee facility tend to support this.[3]

The Gallatin, Tennessee conclusion (Section 5.1) tests also showed decreased lead and cadmium emissions. However, it is not clear just what effects on toxic metal emissions can be generally predicted. Toxic metals such as lead, cadmium, and chromium are found in significant proportions in the combustible fraction of waste in the form of colorants, paints, stabilizers, and inks.[6] Therefore, removal of iron, aluminum, and other non-combustibles from the waste may not eliminate emissions of the heavy metals from incinerated waste.

The Swedish Environmental Protection Board has estimated that 5 percent of Sweden's annual cadmium emissions can be attributed to nickel-cadmium batteries; therefore, removal of batteries from the waste stream should result in a decrease in cadmium-containing ash and particulate matter formed in the combustion process.[7] Even more significant is the Swedish government's estimate of mercury emissions due to combustion of alkaline pyrolusite batteries. Alkaline batteries contain about 1 percent mercury by weight.[8] Of an estimated 5,400 kg of mercury emitted in 1984 in Sweden, approximately 2,200 kg was attributed to combustion of batteries and 1,100 kg to combustion of other mercury-containing waste. With goals of reducing both cadmium and mercury levels in the Swedish environment, a campaign to separate batteries from municipal waste has now begun. Environmental hazards posed by batteries have also been noted at a combustor in Wurzburg, West Germany, where a special bin was provided for battery disposal.[9] In the case of mercury emissions, these separation practices may represent the most effective means of reducing emissions, because test data indicate only 30 to 40 percent control of mercury emissions by available control technologies (see "Municipal Waste Combustion Study: Flue Gas Cleaning Technology.")

Separation of other toxic materials such as paints and pesticides, possibly could decrease the potential for toxic materials emissions from combustion. However, the significance of emissions decreases that could be achieved through such measures is not presently clear. Such measures could help diminish, and certainly would not be expected to exacerbate, environmental effects of combustion.

Hydrochloric acid emissions are also of concern in the operation of municipal waste incinerators. Paper and plastics have been shown to be major sources of chlorine in the waste and are, therefore, assumed to be major contributors to HCl emissions.[10] With that in mind, one may presume that removal of significant quantities of paper and plastic from the waste stream should reduce HCl emissions significantly. But, there are also significant quantities of chlorine in other parts of the refuse,[11] such as food, so, it is not clear what effect removal of large quantities of paper and plastic would have on HCl emissions from combustion. No confirming data on reducing HCl through removal of paper and plastic were found.

Another issue raised with chlorine in the waste is the question of its contribution to the formation of chlorinated organics, particularly chlorinated dibenzo-para-dioxins (CDDs) and chlorinated dibenzofurans (CDFs), in the combustion process. The presence of CDDs and CDFs in emissions from municipal waste combustion is well documented.[12] However, despite extensive study, the mechanism (or mechanisms) leading to formation of these compounds is not well understood. A discussion of potential CDD/CDF formation mechanisms is given in the volume titled "Municipal Waste Combustion Study: Combustion Control of Organic Emissions."

The potential for PVC-bearing wastes to act as a precursor for CDD/CDF emissions from municipal waste combustors has been studied by several researchers. Swedish laboratory experiments demonstrated that CDDs and CDFs are formed from PVC under pyrolytic conditions.[12] Furthermore, in research sponsored by the Ontario Ministry of the Environment and conducted by F.W. Karasek at the University of Waterloo in Ontario, Canada, catalytic formation of CDDs and CDFs was observed when the thermolysis products of PVC combusted in air were heated to 300°C in the presence of clean flyash.[14] The results of these experiments have not yet been published, pending attempts to reproduce these findings.

Despite these findings which tend to link PVC with CDD/CDF formation, it is unclear how separation and removal of PVC-bearing waste would affect emissions of CDDs and CDFs from municipal waste combustors. In one recent study, flyash samples from 6 municipal waste combustors in 4 countries were collected and analyzed for CDDs and CDFs using the same analytical procedures.[13] The lowest concentrations of CDDs and CDFs were found in a flyash sample from a Japanese waste combustor where refuse was first sorted to remove metal and plastic wastes before combustion. The remaining facilities burned unsorted waste. Although the CDD and CDF concentrations were found to be lower in the Japanese combustor flyash samples, the isomer patterns in all of the combustor flyash samples were found to be similar, indicating that the same basic mechanisms and precursors were operating at all facilities. Swedish researchers also noted a similarity in the pattern of individual CDD and CDF isomers measured in samples of emissions from municipal waste combustors and from laboratory pyrolysis experiments involving PVC and other chloroaliphatic compounds, despite the wide variation in chlorine content (1 to 90 percent).[12]

Research to date has shown that PVC is capable of producing CDDs and CDFs under laboratory conditions. However, the mechanism by which this transformation occurs is not clearly defined. More research is needed to explain the role of PVC and other potential pathways and reactants that may contribute to formation of CDD/CDF in municipal waste combustors. Based on the recent studies cited above, it appears unlikely that 100 percent removal of PVC and other plastic waste materials from municipal waste before combustion would eliminate emissions of CDDs and CDFs from municipal waste combustors. For this reason, the importance of combustion optimization and effective flue gas controls as a means for reducing CDD/CDF emissions must continue to be emphasized. These measures are described in more detail in two other volumes titled, "Municipal Waste Combustion Study: "Combustion Control of Organic Emissions;" EPA/530-SW-87-021c and "Municipal Waste Combustion Study: Flue Gas Cleaning Technology;" EPA/530-SW-87-021d.

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